U. S. DEPT. OF COMMERCE
ENVIRONMENTAL SCIENCE SERVICES ADMINSTRATION
WEATHER BUREAU

C. R. Technical Memorandum 13

CENTRAL REGION TECHNICAL MEMORANDUM 13

DIURNAL SURFACE GEOSTROPIC WIND VARIATIONS OVER THE GREAT PLAINS

Kansas City, Missouri
Mar. 1967

U.S. DEPARTMENT OF COMMERCE · ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION · ESSA

I. INTRODUCTION

One might conclude from an examination of sea-level pressure charts that little diurnal change takes place in the surface geostrophic wind, even over sloping terrain such as the Great Plains. However, evidence will be presented here which indicates that the usual diurnal temperature variation in the boundary layer over the Great Plains leads to an appreciable diurnal variation in the surface geostrophic wind.

This paper reports the results of a study of diurnal variations of the component of the surface geostrophic wind parallel to the smoothed earth's contours using hourly data from Great Plains stations and a method of computation which does not involve reducing pressures to sea level or to any other level or constant-pressure surface. For comparison, the geostrophic wind was also computed from the sea-level pressures.

2. EXPLANATION OF THE PHENOMENON

In this section an explanation will be offered which outlines how diurnal temperature variations can bring about diurnal variations in the geostrophic wind in the boundary layer over the Great Plains.

A simple way of looking at the problem is to consider the thermal winds which are set up in the boundary layer. In the daytime, colder air is encountered as one proceeds isobarically eastward from a point on the earth's surface, which means that the south component of the geostrophic wind decreases with height. At night the opposite situation prevails, since warmer air is encountered as one moves away from the slope isobarically.

This effect is akin to that which produces mountain and valley winds, or "drainage" or "gravity" winds, with the obvious difference that the slope of the Great Plains is much smaller. The horizontal dimensions are much larger, however, so that the phenomenon should appear even in a large-scale analysis of the geostrophic wind field.

To treat the problem mathematically, it will be convenient to use the altimeter correction system of Bellamy (1). In this system the hydrostatic equation may be written

$$S^{*} = \frac{\partial D}{\partial Z_p} \qquad (1)$$

Here, $D = Z - Z_p$, $S^{*} = (T^{*} - T_p)/T_p$, where Z is height, Z_p is pressure altitude, T^{*} is virtual temperature, and T_p is temperature in the standard atmosphere.

It will be assumed that overlying the boundary layer there is a uniform atmosphere in which there is no horizontal pressure gradient and which has a uniform value of .01 for S^{*}. In the boundary layer, which is assumed to be 1 km thick, S^{*} is assumed to be .02 at the ground at the time of maximum temperature, decreasing linearly (with respect to Z_p) to the value of .01 at the top. At the time of minimum temperature the value of S^{*} will be assumed to increase linearly from -.04 at the ground to .01 at the top (see Fig. 1). These conditions correspond to a diurnal temperature range of about 32F, a rather large value chosen for convenience and emphasis.

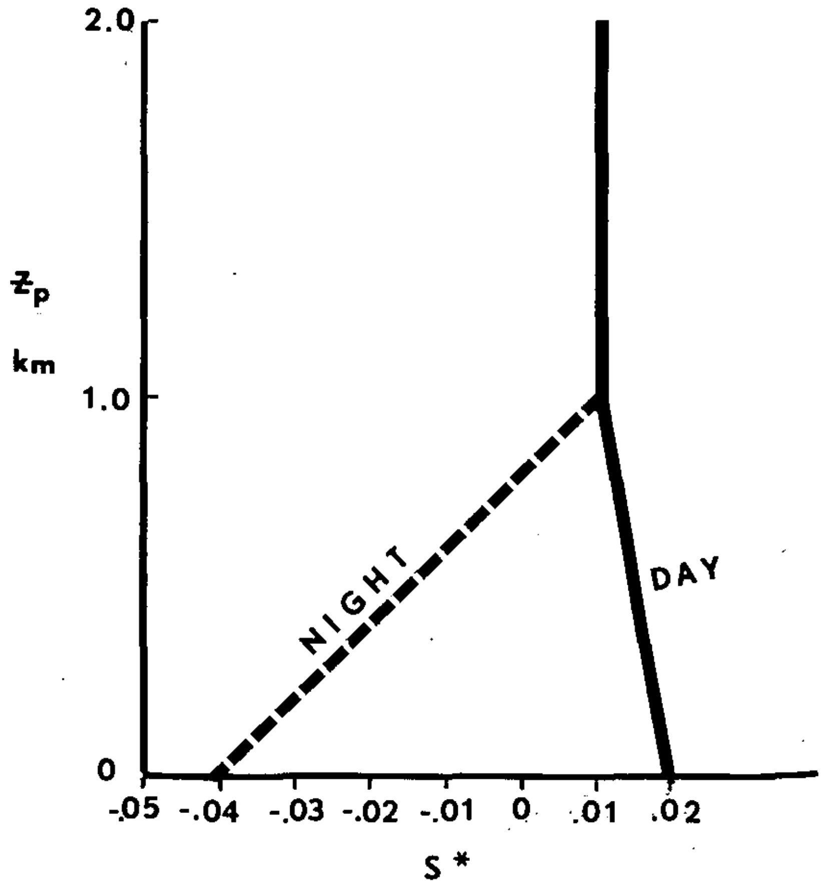


Figure 1 - Assumed distribution of specific virtual temperature anomaly (S^*) with height in and above the boundary layer at the time of minimum surface temperature (night) and at the time of maximum surface temperature (day).

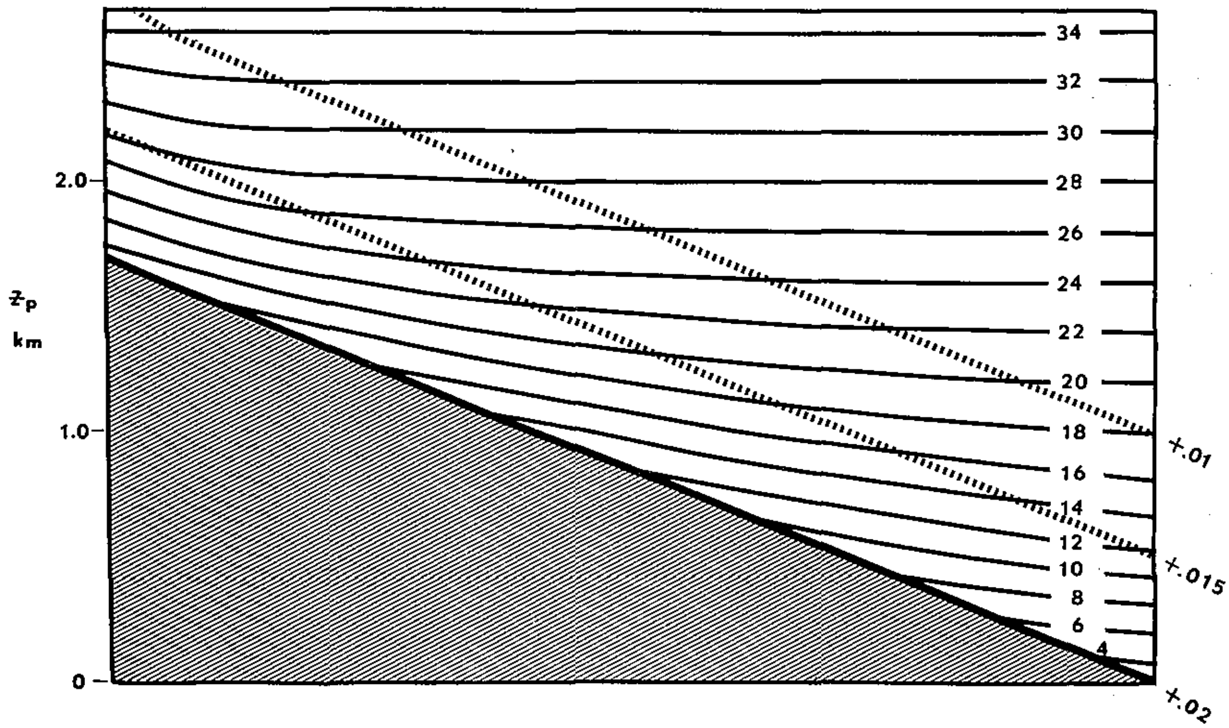
This situation is depicted in Figs. 2 and 3, in which are also drawn isopleths of the D value corresponding to the assumed S^* distribution. In accordance with the assumption of no horizontal pressure gradient in the atmosphere above the boundary layer, the isopleths of D are coincident with the isobars (Z_p = constant) in this region both night and day. In the daytime (Fig. 2) the D isopleths close to the ground tend to become more parallel to the terrain slope. As one proceeds away from the slope isobarically (to the right in the diagram) higher values of D are encountered, thus corresponding to a south component of the geostrophic wind if the plane of the figure is oriented east-west. On the other hand at night (Fig.3) the isopleths of D are bent around by the temperature gradient in the boundary layer so that lower values are encountered as one moves eastward away from the slope. This corresponds to a north component of the geostrophic wind.

3. METHOD OF COMPUTATION OF GEOSTROPHIC WIND COMPONENT

Equation (10) of a paper by the author (2), which is

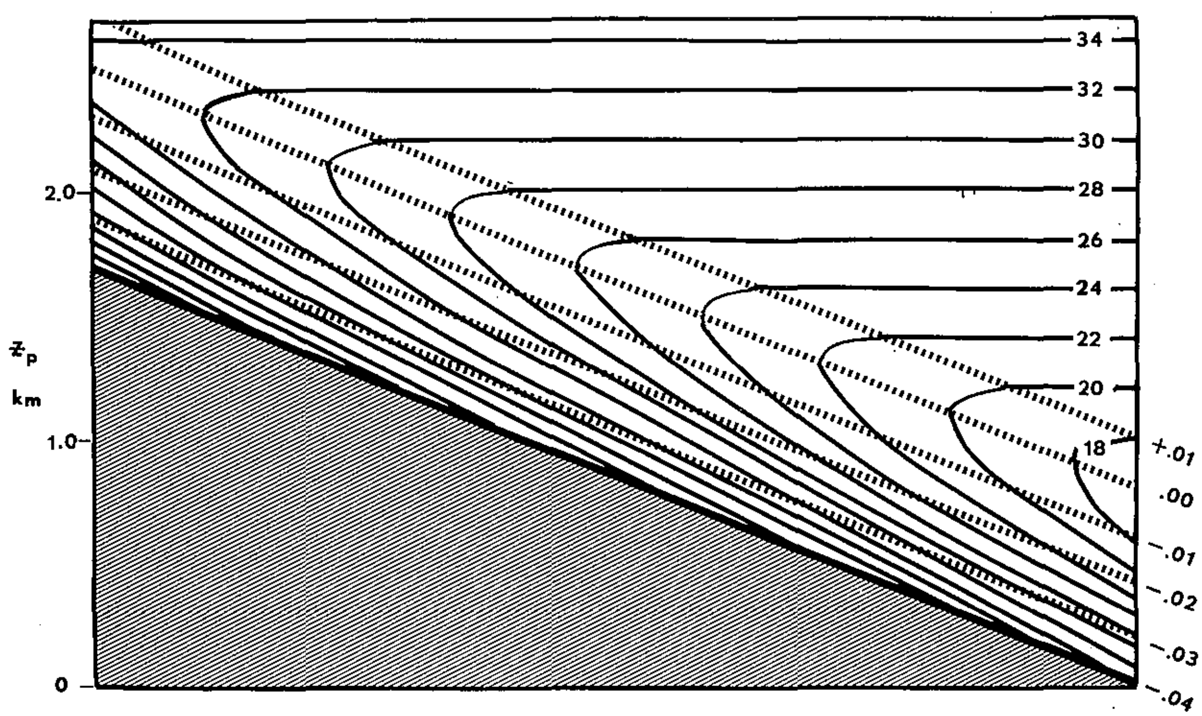
$$\nabla_p Z = \nabla D - S^* \nabla Z_p \qquad (2)$$

was used to compute the horizontal pressure force. Here the subscript p indicates the derivative is to be taken in an isobaric surface, whereas derivatives without subscripts are to be taken along the sloping terrain.



DAY

Figure 2 Cross section showing D values (meters, solid lines) and S* (dashed lines, except at earth's surface) for day time under assumed conditions over sloping terrain.



NIGHT

Figure 3 Same as for Figure 2 but for night conditions.

From (2) we may write the geostrophic wind equation as

$$v_{gn} = \frac{g}{f} \left(\frac{\partial D}{\partial x} - S^{*} \frac{\partial Z_p}{\partial x} \right) \qquad (3)$$

where v_{gn} is the geostrophic wind component in the positive y direction, where the x-axis passes through two selected stations. Here g is the acceleration of gravity and f is the Coriolis parameter.

The altimeter settings, temperatures, and dew point temperatures reported in the airways observations as well as the heights of the stations were used to compute D, S^{*}, and Z_p in equation (3). Finite differences were used to replace the derivatives in (3), using values computed at the two stations. S^{*} was computed as the average of the values at the two stations.

It is of interest to assess the approximate magnitude of the diurnal variation of the two terms within the parentheses of (3). Since the D value depends only on the station pressure and station elevation, one would expect the diurnal variation of the first term to be small. A diurnal temperature range of 20F corresponds roughly to a range of .04 in S^{*}. For a terrain slope of 1 in 500 which is typical of the Great Plains, the second term corresponds to a diurnal range in the geostrophic wind of about 18 knots at 35 degrees latitude.

4. CASE STUDIES

A. Amarillo-Oklahoma City line - June 1966

In order to isolate the effects of the diurnal temperature cycle from those of traveling disturbances in the pressure field, the component of the surface geostrophic wind normal to the Amarillo-Oklahoma City line was averaged over the thirty days of June 1966 for each hour of the day. This line is nearly perpendicular to the smoothed contours of the terrain, and the terrain slope along it averages about 1 in 530. A persistent southerly flow was present during most of the month in this area. The solid line in Fig. 4 shows the geostrophic component as computed from equation (3).

It will be seen that there is a definite diurnal cycle in the geostrophic wind, with a minimum at 0600 CST and a maximum at 1600 CST. The range from night to day is approximately 18 knots, with the afternoon speed more than double that of the early morning. The shape of the curve is quite similar to a normal temperature trace, suggesting that it is the second term within the parentheses of equation (3) which is primarily responsible for the diurnal fluctuation of the geostrophic wind component, which is in agreement with our previous discussion. Further confirmation of this is provided by the computations shown in Fig.5, which represent a fictitious geostrophic wind component computed from only the first term within the parentheses of equation (3). Here the speeds vary no more than about 2 knots during the 24 hours when averaged over thirty days. The absolute value of this fictitious wind is determined by how the standard

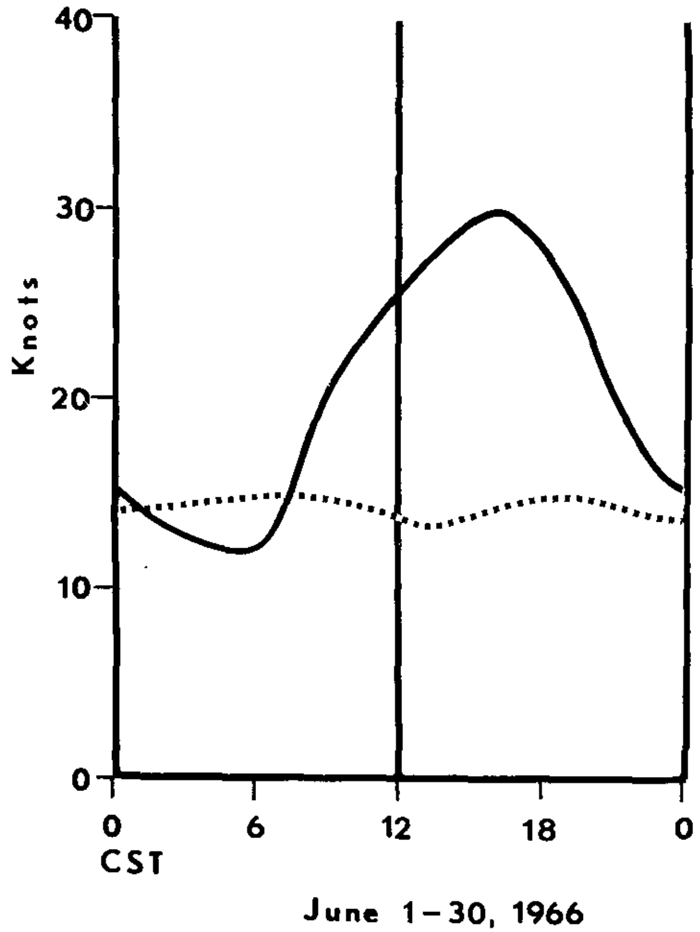


Figure 4 Surface geostrophic wind component normal to Amarillo-Oklahoma City line as computed from equation (3) (solid line) and from sea-level pressures (dashed line) averaged for the entire month of June 1966.

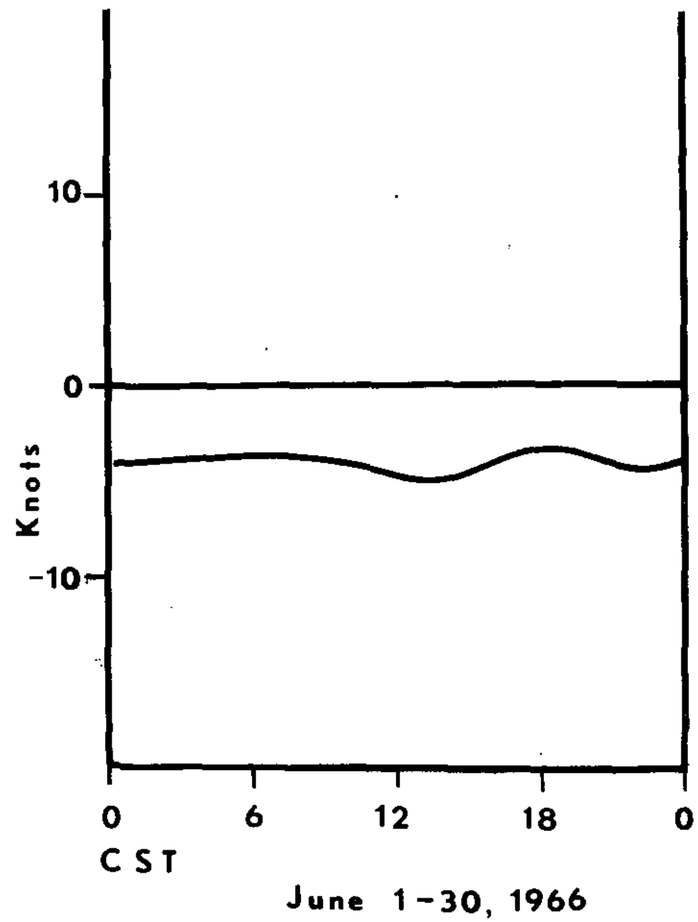


Figure 5 Same as solid line in Figure 4, except that only the first term within the parentheses of equation (3) was used.

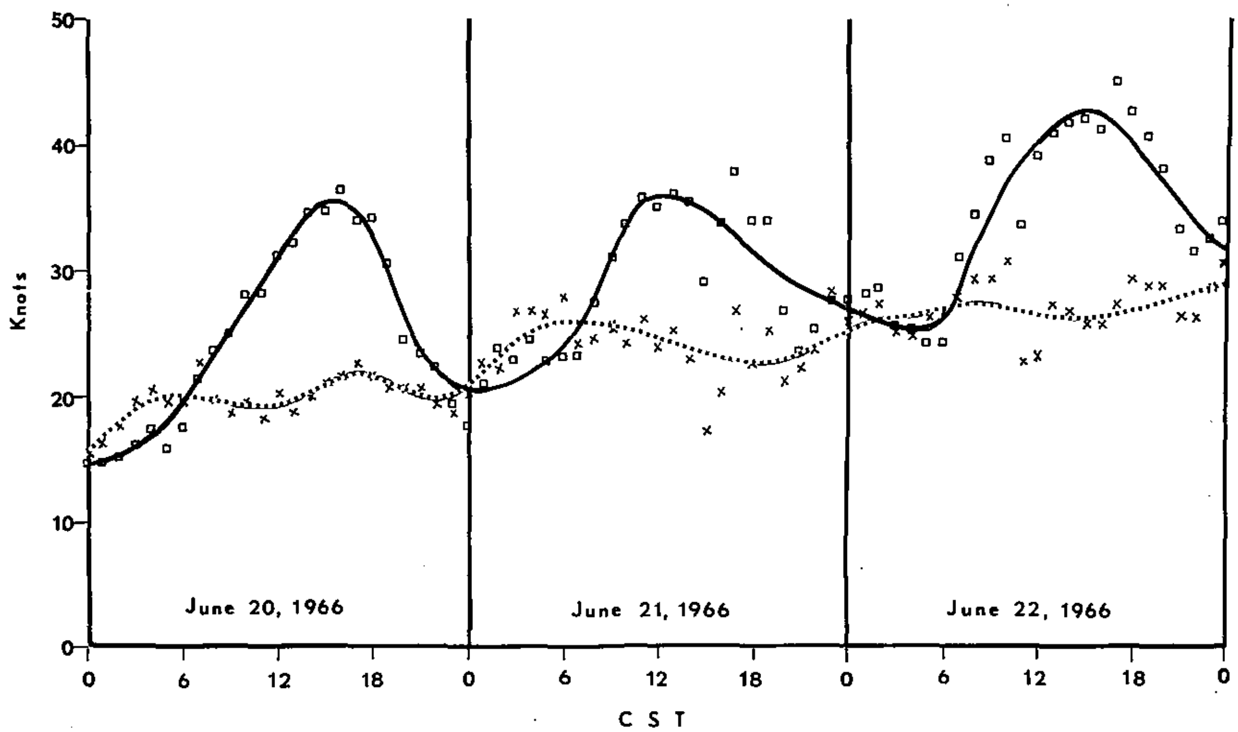
atmosphere is defined, and is therefore of no particular interest.

The geostrophic wind component computed from the sea-level pressures (dashed line in Fig. 4) also does not vary more than about 2 knots, and the curve looks very similar to that in Fig. 5. An explanation for the absence of any pronounced diurnal variation in the geostrophic wind computed from the sea-level pressures is that an average temperature consisting of the present temperature and that 12 hours earlier is used in reducing to sea level. This effectively masks diurnal variations which according to equation (3) are real.

It will be noted from Fig. 4 that the sea-level pressure geostrophic wind averaged over 24 hours is about 6 knots smaller than the 24-hour average computed from equation (3). A reason for this is that the term introduced into the pressure reduction scheme to account for the "plateau effect" has a differential effect over sloping terrain, since it is a function of station elevation. When the temperature is above the annual mean, as it was in this case, this term will be positive and larger at the higher station than at the lower, which means that the pressure difference due to the plateau effect will correspond to a fictitious north geostrophic wind component.

During the latter part of June the southerly geostrophic flow persisted uninterrupted by frontal passages for many days. A six-day period from June 20 through June 25 is shown in Fig. 6. A diurnal cycle in the geostrophic wind as computed from equation (3) is clearly evident, with a night-to-day range of about 18 knots.

Amarillo - Oklahoma City Line



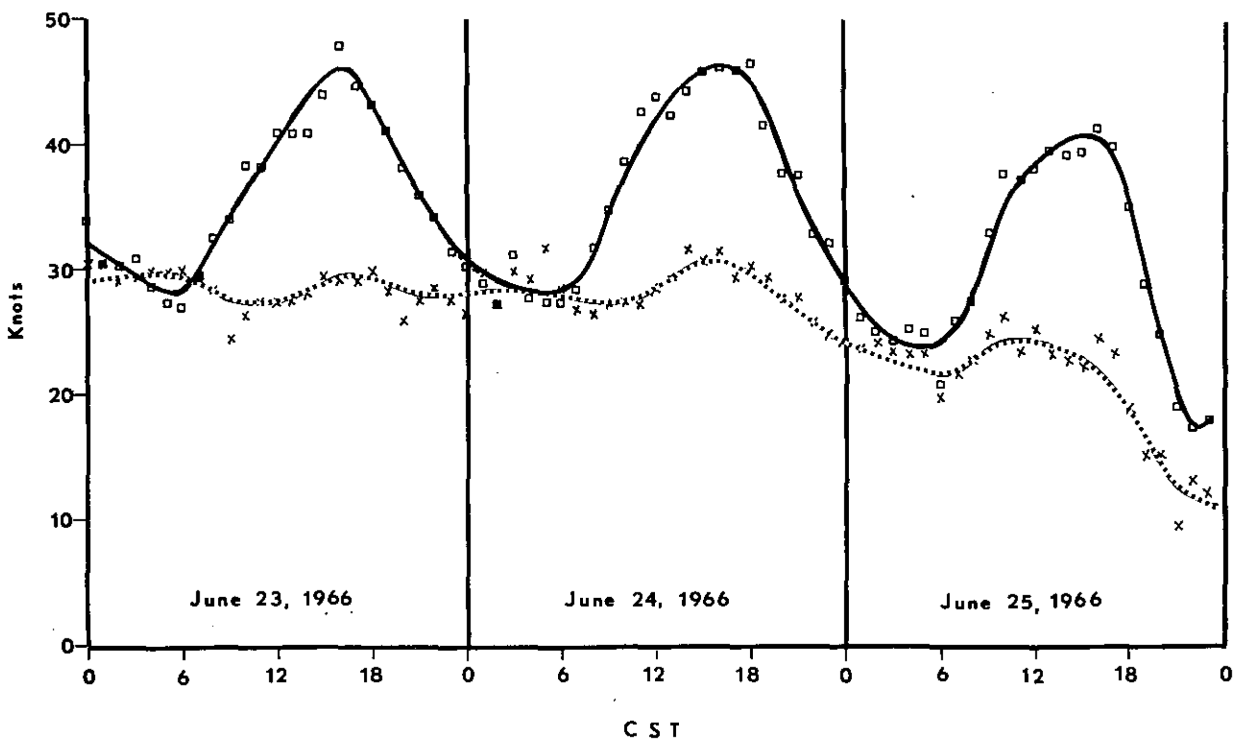


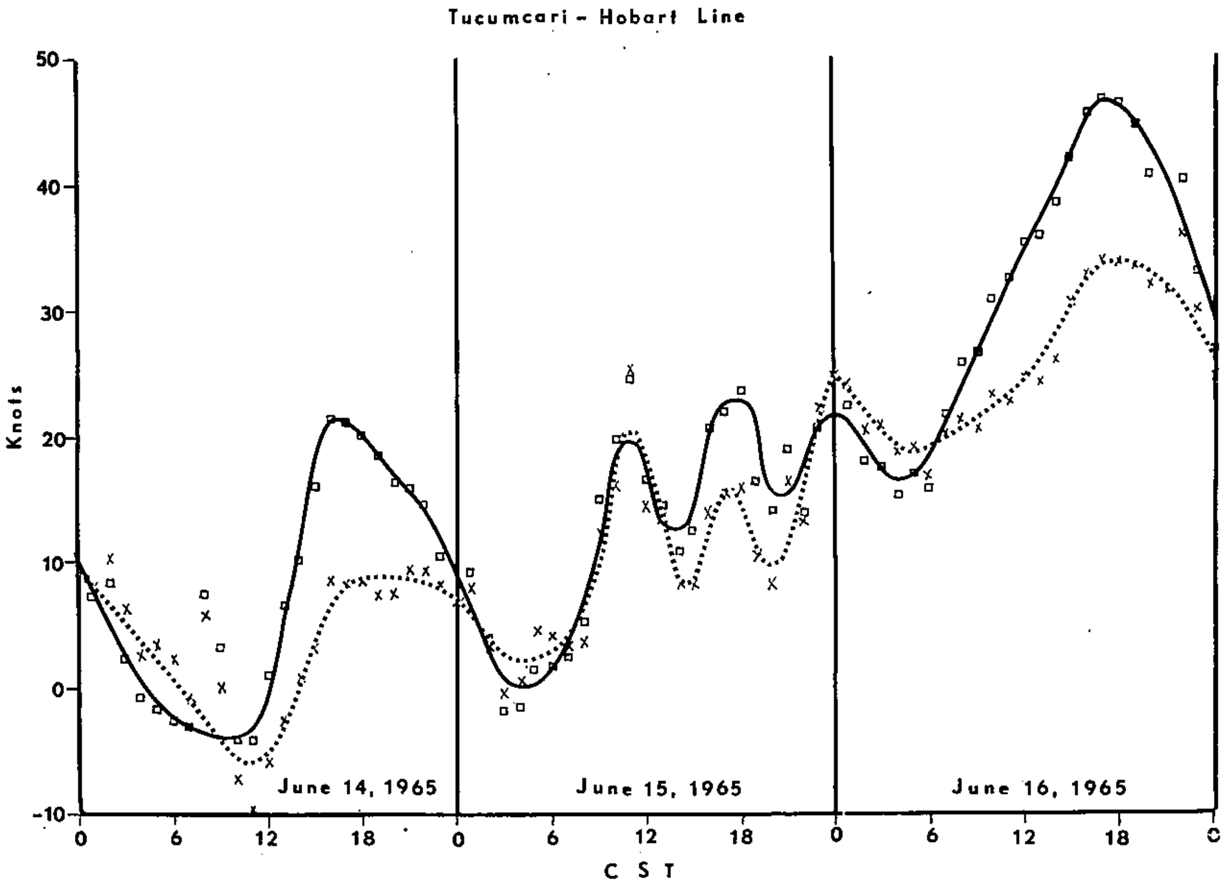
Figure 6 Same as Figure 4, but for individual days of June 20-25, 1966.

This diurnal cycle is superimposed on a trend toward an increasing southerly component on the first three days reaching a maximum on the 23rd and 24th, then decreasing again on the 25th. As in the monthly average, no appreciable diurnal cycle is apparent in the sea-level pressure geostrophic wind.

B. Tucumcari, New Mexico-Hobart, Oklahoma line - June 14-19, 1965

This was a period during which heavy rains fell in Eastern Colorado (Scientific Services Division (4)). A strong southeasterly low-level flow persisted during the period, reaching a maximum the night of June 16-17. The computed surface geostrophic wind component normal to the Tucumcari-Hobart line for the six-day period is shown in Fig. 7 (solid line). Also shown is the sea-level geostrophic component (dashed line).

It will be seen that there is a definite diurnal cycle in the geostrophic wind, with a minimum usually occurring around 0500 CST, and a maximum around 1700 CST. The maximum geostrophic speed occurred on the afternoon of June 16, reaching a value of about 46 knots. As mentioned in reference (4) the surface wind at Amarillo began gusting on the afternoon of the 16th, and continued gusting until 0300 CST June 17. The peak gust reported (33 knots) was at 0100 CST June 17. The average night-to-day range in the geostrophic wind speed was about 24 knots, somewhat above the estimate of 18 knots previously made. Particularly noticeable is the rapid and steady increase from early morning to late afternoon on June 16. This is more than can be explained by surface heating alone, and a traveling



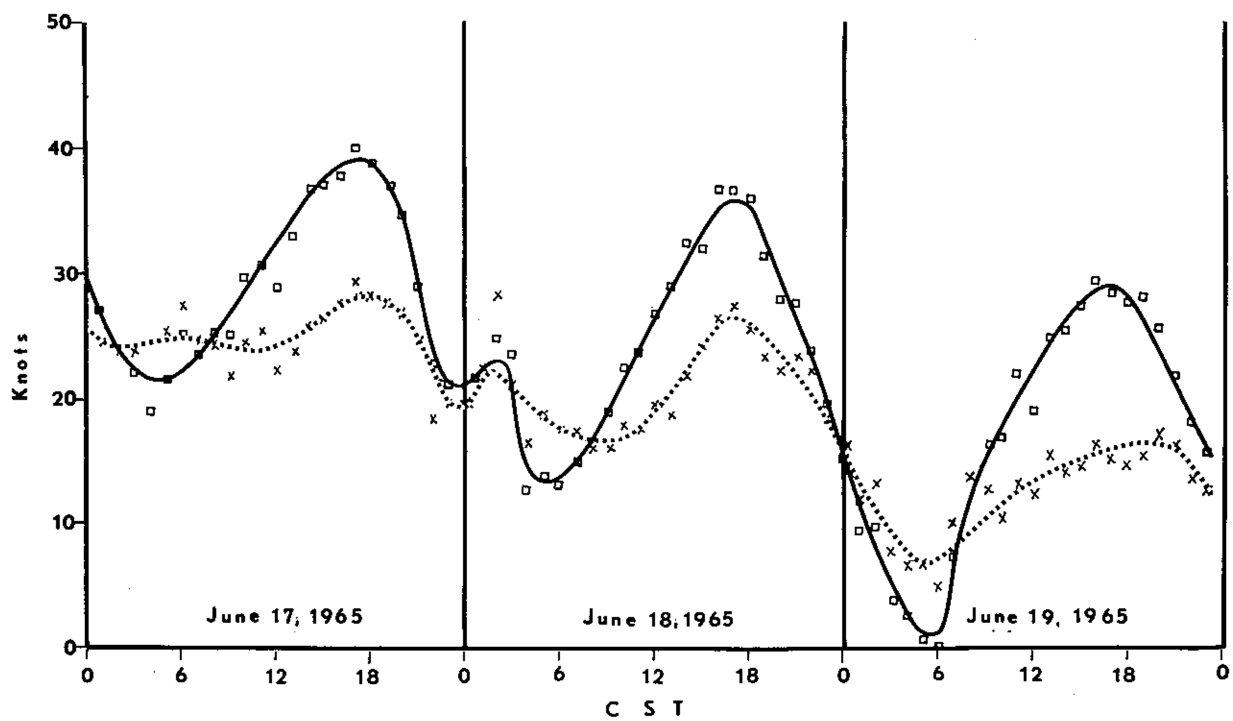


Figure 7 Same as for Figure 4, but for Tucumcari, N. M. - Hobart, Oklahoma line for individual days of June 14-19, 1965.

disturbance or some other effect must have also played a role.

C. Cross-sections for June 8-10, 1958

Figures 2 and 3 show in a simplified, hypothetical case, how geostrophic wind variations can arise in the boundary layer. Earlier in this section were presented some actual computations of the surface geostrophic wind component, but they did not provide much information as to the realism of the vertical structure shown in the hypothetical case. Fig. 8 is reproduced from a paper by the author (3) in order to show an actual case in two dimensions. The isopleths of S^* tend to parallel the earth's surface on the nighttime (1200 GCT, diagrams c and e) sections, with the lowest values being at the ground. The daytime (0000 GCT, diagrams b, d, and f) sections show this inversion to be destroyed, with the maximum values of S^* being found at the ground. The night-to-day change in the orientation of the isopleths of S^* near the ground has the effect that the sign of the vertical geostrophic wind shear in the lowest 3 to 4000 ft of the atmosphere changes from night to day. It follows that there must be a diurnal geostrophic wind variation either at the top of this layer, or at the bottom, or at both places. It is apparent from the cross-sections that the maximum variation takes place at the ground.

6. CONCLUSIONS

There can be little doubt but that a significant diurnal variation in the surface geostrophic wind component parallel to the terrain contours takes place over the Great Plains under clear-sky conditions. Its magnitude is

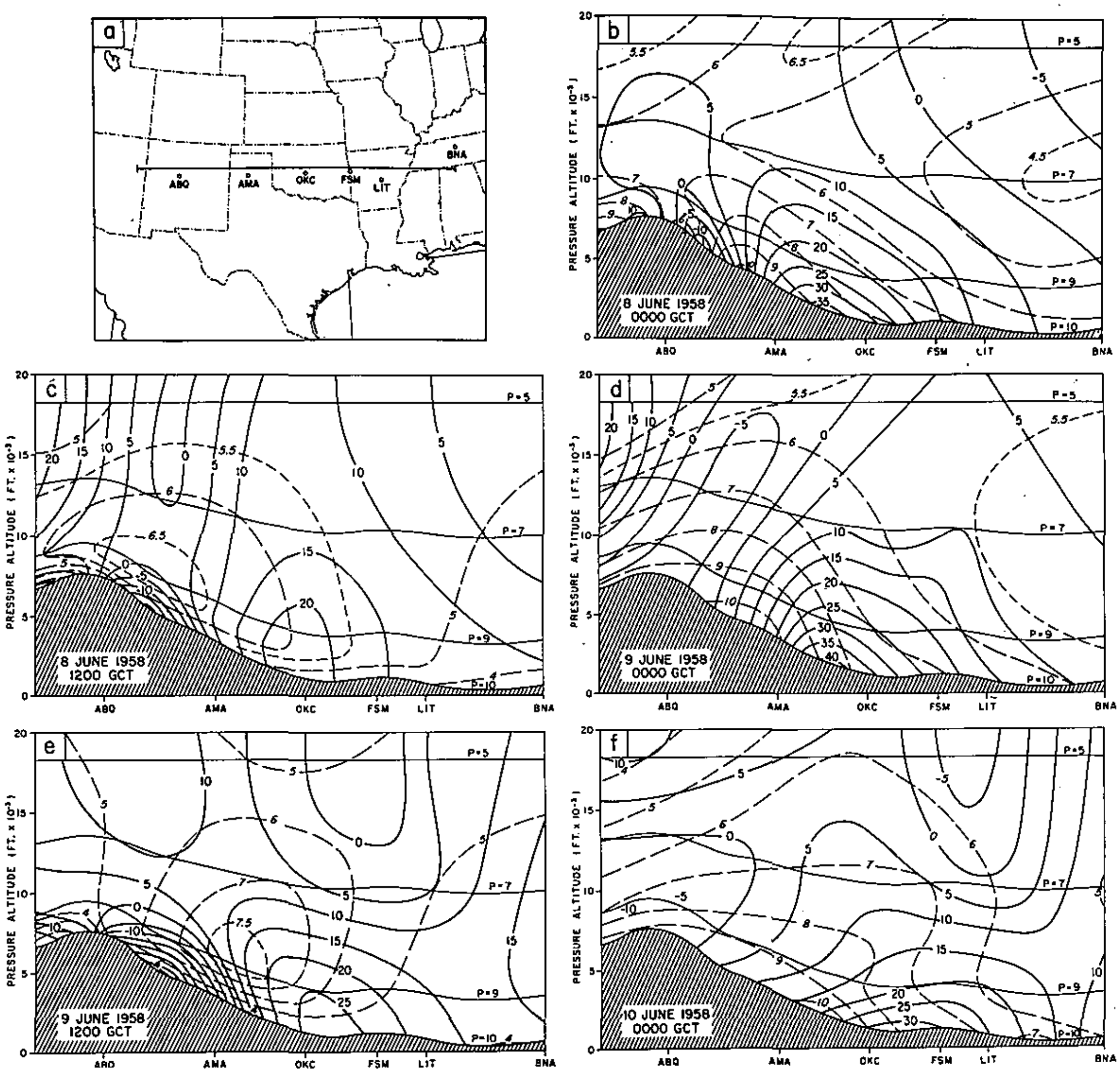


Figure 8 Cross sections oriented along the line shown in diagram a. Dashed lines are isopleths of S^* (in percent) and solid lines are isotachs of the geostrophic wind component (in knots) normal to the sections. From Ref. (3).

too large to be considered negligible in any attempt to explain or model the behavior of the real wind. It is beyond the scope of this paper to attempt to describe what variations there might be in the real surface wind, but one might expect that over the Great Plains under southerly flow diurnal speed variations are not due entirely to diurnal variations in turbulent mixing, the usual explanation. Under conditions of weak pressure gradients and clear skies, one might expect that an appreciable diurnal shift in wind direction might take place due to the diurnal variation of the geostrophic wind.

Another question is what role these geostrophic wind variations play in the formation of boundary layer maxima in the vertical profile of the wind speed (low-level jets) which are frequently found over the Great Plains during the nighttime hours. At the level of the observed maxima (600 m or so) in these jets, the amplitude of the geostrophic variations is perhaps only half that at the ground, but turbulent mixing during the day would mean that the larger amplitude found at the ground would exert an influence through the entire boundary layer. A paradox is the fact that under southerly flow the geostrophic wind speed is at a maximum during the late afternoon, whereas at the 600 m level the real wind speed typically reaches a maximum during the night. This is a subject worthy of further investigation.

REFERENCES

1. J. C. Bellamy, "The Use of Pressure Altitude and Altimeter Corrections in Meteorology," Journal of Meteorology, Vol. 2, No. 1, Mar. 1945, pp. 1-79.

2. W. E. Sangster, "A Method of Representing the Horizontal Pressure Force Without Reduction of Station Pressures to Sea Level," Journal of Meteorology, Vol. 17, No. 2, Apr. 1960, pp. 166-176.

3. ______________,"A Modified 'Sigma' System of Coordinates," Scientific Report No. 1, Contract No. AF19(604)-7230, Dept. of Meteorology, U. of Chicago, Sept. 1960.

4. Scientific Services Division, "Heavy Rains in Colorado, June 16 and 17, 1965," Central Region Technical Memorandum 4, U. S. Weather Bureau, Kansas City, Mo., July 1966.